5Gbps HG 0,1 and HG 0,3 Optical Mode Division Multiplexing for RoFSO

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***Abstract* — Radio-over-free-space optics (Ro-FSO) technology harnesses the large capacity of optical fiber and the mobility native to wireless networks. To increase the capacity of Ro-FSO networks, this work introduces a new optical mode division multiplexing (MDM) scheme for Ro-FSO by incorporating optical Hermite-Gaussian modes HG 0, 1 and HG 0, 3 for transmitting two distinct 2.5 Gbps data modulated on 10 GHz radio subcarriers. Signal-to-noise ratios and bit-error-rates show successful 2 x 2.5Gbps data transmission of 10GHz radio-modulated subcarriers over the two HG optical carriers through a 800m free-space channel.**

Keywords—mode division multiplexing (MDM), space diviosn multiplexing (SDM), eigenmodes, free-space optics (FSO), Hermite-Gaussian mode, radio over free space (Ro-FSO), heteregenous networks, digital-divide, underserved areas

I. INTRODUCTION

The evolution towards information-centric societies and advent of interactive triple-play applications have prompted increasing demand for data capacity and transmission quality in wireless networks. Network operators have made huge investment in infrastructure, providing coverage to several urban areas from base stations typically connected by an optical fiber backbone or copper cables. Using copper cables merely provides 2Mb/s access per pair, significantly below Gigabit Ethernet data rates. Using an optical fiber backbone allows base stations to carry radio signals over a faster optical carrier to other base stations and then converted back to radio signals at the central station [1, 2].

To harness the large capacity of optical fiber and the mobility native to the wireless networks, the integration of wireless and optical networks is a promising direction. Although optical fiber provides higher data rates for realizing Gigabit Ethernet, laying cables is increasingly unattractive in cities and regulated by local authorities in order to mitigate disruption as costs are often prohibitive [3-5]. The drive for multi-gigabit data rates in radio networks is creating new opportunities for free-space optics (FSO) technology in radio networks. Ro-FSO enables seamless integration of base stations in radio networks with optical core backbones without laying expensive optical fiber cable. Ro-FSO is compatible with existing mobile cellular architectures and boasts of advantages such as faster rollout due to less cabling, high bandwidth, low attenuation losses and low power consumption [3, 6]. Ro-FSO networks may be useful for network redundancy, disaster recovery and provision of network services to underserved areas [3, 7, 8].

Recent Ro-FSO advancements for increasing data capacity include shifting carrier frequencies from the microwave band to the millimeter-wave band [1, 3, 9]. Millimeter-wave band technology requires micro-cells and pico-cells which cover a limited area in high-density areas but consume less power and cost less than larger macro-cell towers [3, 9]. To connect the rapidly growing micro-cells and pico-cells, free-space space optics may be used as the backhaul, forming a ubiquitous platform for heterogeneous radio-optical operation without disruptive and expensive optical fiber cabling [1, 3].

An emerging multiplexing scheme, termed mode division multiplexing (MDM), uses eigenmodes to transport independent channels simultaneously. Although MDM has been demonstrated in fiber communications using spatial light modulators to generate specific mode profiles [10-12], optical signal processing [13-15], few mode fiber [16, 17], photonic crystal fibers [18] and modal decomposition [19], MDM is still in its infancy in Ro-FSO systems. Preliminary work on MDM for Ro-FSO have adopted Laguerre-Gaussian (LG) modes [4] and orbital angular momentum (OAM) modes [20].

This paper introduces a new MDM scheme based on Hermite-Gaussian (HG) modes. The paper proceeds as follows. Section II elucidates the design concept of the MDM model and simulation parameters. Section III describes the results and discussions, followed by the conclusion in Section IV.

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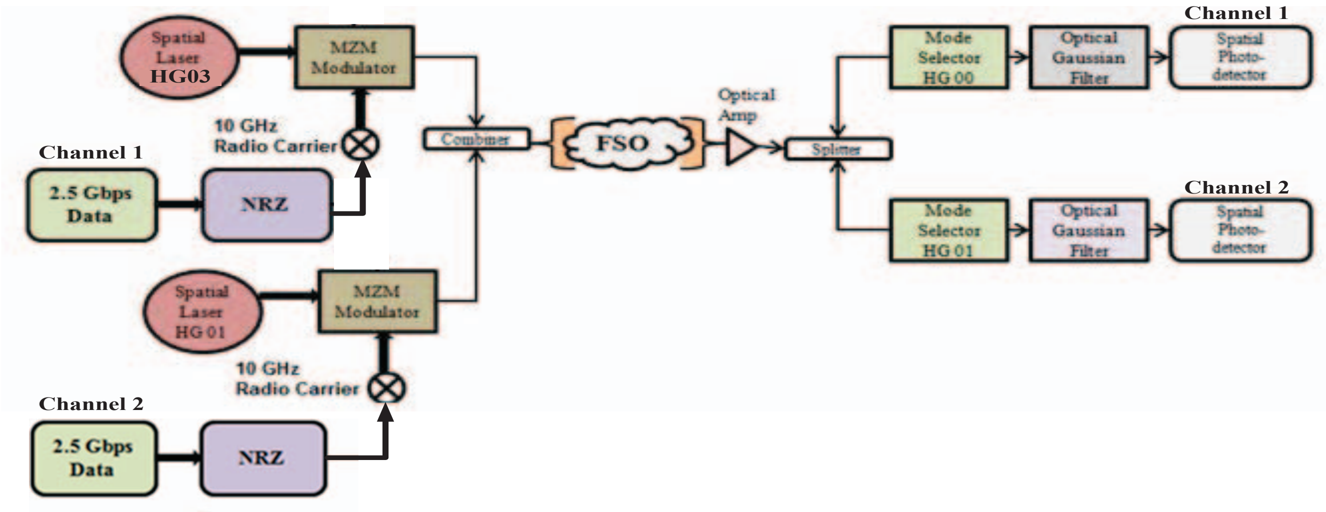


Fig. 1 Proposed MDM based Ro-FSO model

II. Methodology

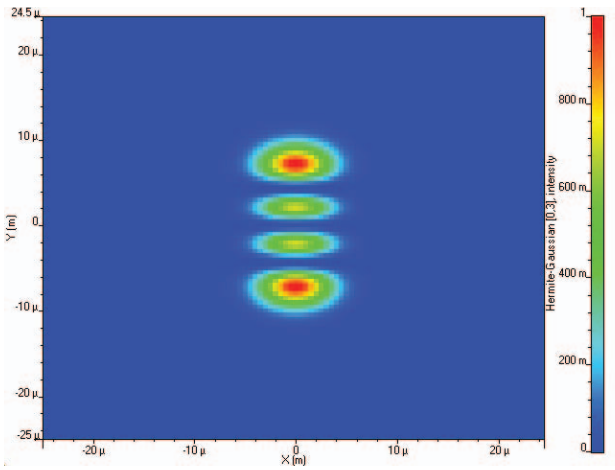
A new MDM architecture for Ro-FSO based on Hermite-Gaussian (HG) modes is designed in Optisystem software, as shown in the block diagram in Fig. 1. The proposed architecture comprises two distinct non-return-to-zero (NRZ) encoded data streams modulated on a 10GHz subcarrier over two separate 2.5GHz 850nm optical carriers on Hermite-Gaussian modes HG 0,3 and HG 0,1 transmitted through a 1km-long free-space channel. Hermite-Gaussian mode HG 0,3 is used as the optical carrier in Channel 1 and HG 0,1 as the optical carrier Channel 2 as shown in Fig 1. The HG mode is described mathematically [28] as:

$$\psi_{m,n}(r,\phi)=H_m\left(\frac{\sqrt{2}x}{w_{o,x}}\right)\exp\left(-\frac{x^2}{w_{ox}^2}\right)exp\left(j\frac{\pi x^2}{\lambda R_{ox}}\right)\times H_n\left(\frac{\sqrt{2}y}{w_{o,y}}\right)\exp\left(-\frac{y^2}{w_{oy}^2}\right)\left(j\frac{\pi y^2}{\lambda R_{oy}}\right) \quad (1)$$

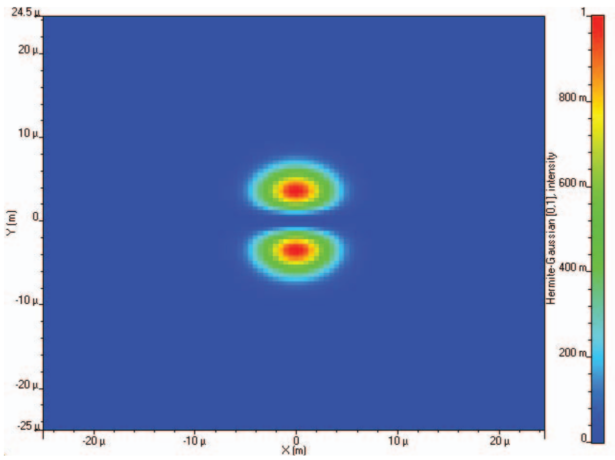
The transverse electric field of the excited Hermite-Gaussian modes for both channels are shown in Fig. 2. The output of two channels are combined, amplified and transmitted through free-space of distances ranging from 200m to 1000m. The link is free from atmospheric turbulences and appropriate for backhaul links of pico-cells and micro-cells for indoor applications. The link equation for free space optics [29] is modeled by:

$$\mathrm{P}_r=\mathrm{P}_t\frac{d_R^2}{(d_T+\theta R)^2}10^{-\alpha R/10} \quad (2)$$

where P_r defines the received power, P_t defines the transmitted power, d_R defines receiver aperture diameter, d_T is the transmitter aperture diameter, θ is the beam divergence, R is the free-space distance and α is the atmospheric attenuation. At the receiver side, the transmitted mode is extracted based on non-interferometric modal decomposition [30]. To retrieve the original baseband signal, the optical signal is fed to low-pass



(a)



(b)

Fig. 2 Transverse electric field of the excited Hermite-Gaussian modes: (a) HG 0, 3 Mode for Channel 1 (b) HG 0, 1 Mode for Channel 2

Gaussian filters and decomposed into the corresponding channel based on correlation with linearly polarized (LP) modes. After modal decomposition, the optical signal from each channel is then fed to a spatial PIN detector to retrieve the radio subcarriers. The radio subcarriers are then down-converted to the original baseband signals.

III. RESULTS AND DISCUSSION

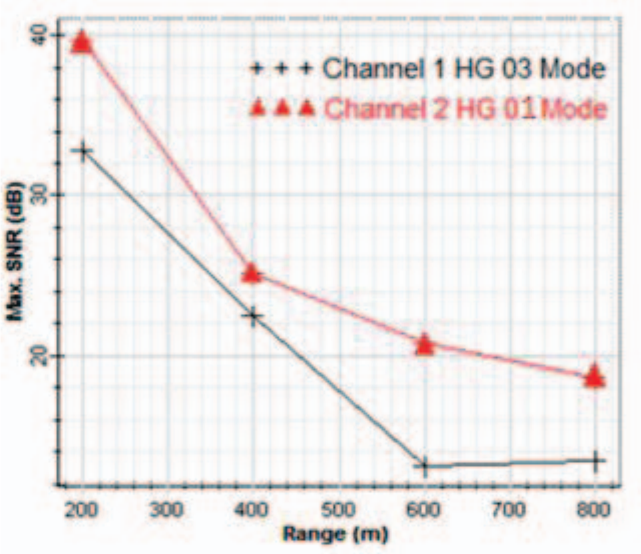
This section presents and discusses findings from our proposed HG MDM-based Ro-FSO system.

Fig. 3 (a) analyzes the signal to noise ratio (SNR) along with the total power at the receiver for both channels. Channel 1 propagating radio-modulated data HG 0,3 mode performs better than Channel 2 propagating radio-modulated data on HG 0,1 mode. The computed values of SNR for Channel 1 are 32.83dB, 22.44dB, 13.11dB and 13.46dB for a for a FSO link of 200m, 400m, 600m and 800m respectively. For Channel 2, the SNR values are 39.66dB, 25.15dB, 20.79dB and 18.64dB for a FSO link length of 200m, 400m, 600m and 800m respectively. Channel 2 (HG 0,1) is on average 5.6dB higher in SNR compared to Channel 1 (HG 0,3).

The total received power for both channels at different free-space distances are compared in Fig. 3(b). An average difference of 5.6dBm is received power is found between Channel 1 (HG 0,3) and Channel 2 (HG 0,1). The received power for Channel 2 stagnate after 800m whereas for Channel 1 the received power continues to deteriorate. The total power received at the photodetector for Channel 1 is computed as -67.17dBm, 77.56dBm, -86.89dBm and -86.54dBm for a FSO link of 200m, 400m, 600m and 800m respectively, whereas for Channel 2 the total received power is -60.34dBm, -74.85dBm, -79.21dBm and -81.35dBm for a FSO link of 200m, 400m, 600m and 800m respectively. Both SNR and received power consistently demonstrate that Channel 2 (HG 0,1) is more robust than Channel 1(HG 0, 3).

The modal decomposition at the receiver is computed in terms of linearly polarized modes for both channels, as shown in Fig. 4. For Channel 1, the power is coupled predominantly into LP 1,2 (62%) and LP 3,1 (23%) modes. For Channel 2, the power is coupled predominantly into LP 1,1 (96%). This agrees with the spatial profiles of the generated HG modes.

Wide eye openings are achieved for both channels, as shown in Fig. 5, which confirm successful transmission of 2 x 2.5 Gbps data through MDM of two 10GHz radio subcarriers on Hermite-Gaussian modes HG 0,3 and HG 0,1 for a free-space link of 800 meters.



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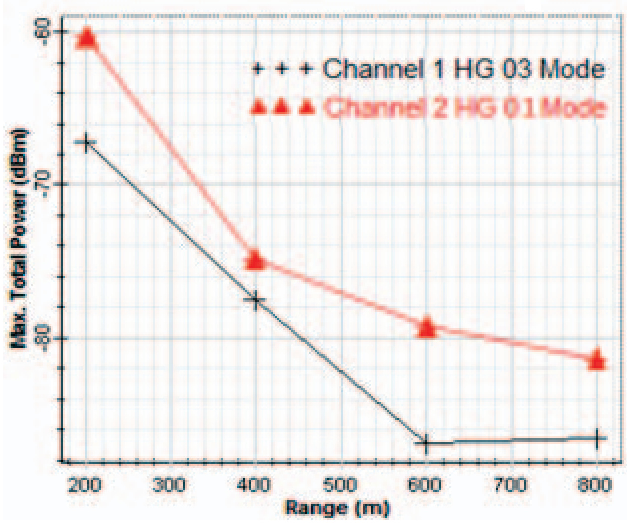
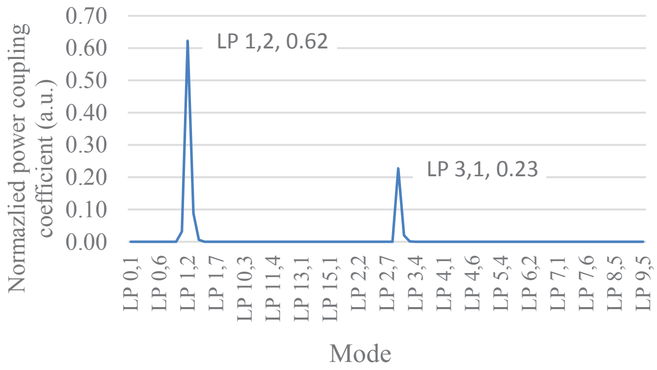


(b)

Fig. 3 Measured Results: (a) SNR versus FSO link distance (b) Total Received Power versus FSO link distance



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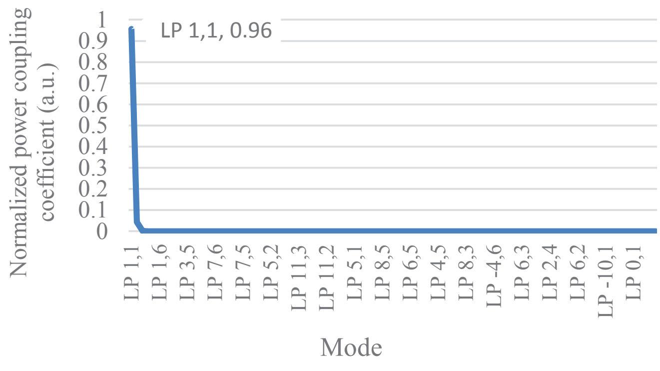
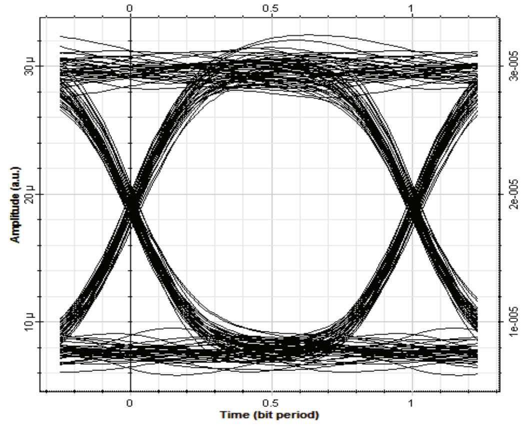
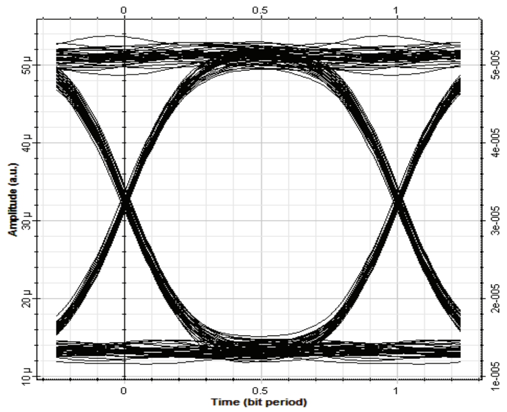


(b)

Fig. 4 Normalized power coupling coefficient versus linearly polarized modes for: a) Channel 1 (b) Channel 2



(a)



(b)

Fig. 5 Eye Diagrams at 800m (a) Channel 1 (b) Channel 2

IV. Conclusion

2 x 2.5 Gbps data transmission on two 10GHz radio subcarriers, each modulated over two 850nm optical carriers on Hermite-Gaussian modes HG 0,3 and HG 0,1 is simulated for a free-space link of 800 meters. SNR, received power, BER and modal decomposition results reveal that that Channel 2 propagating HG 0,1 mode is more robust than Channel 1 propagating HG 0,3. The model may be applied for 5G backhaul links for connecting microcells to each other and to the central station in high-density areas.

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